ARRIVAL TIME OF CORONAL MASS EJECTIONS.

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ABSTRACT

Halo coronal mass ejections (CMEs), originating near the disk center, cause the severest geomagnetic storms. Thus, estimation of the arrival of magnetic clouds in the Earth vicinity is very important in space weather investigation. We describe an empirical model to predict the 1AU arrival time of CMEs. This model is based on the effective acceleration described by Gopalswamy et. al (2000). It was improved by considering halo CMEs for which the space velocities are determined. This allowed us to receive the more accurate estimations. The new model reduces the average prediction error from ≈ 10 to ≈ 5 hours.

Key words: CMEs; space weather ; solar physics.

1. INTRODUCTION

Space Weather is significantly controlled by coronal mass ejections (CMEs) which can affect the Earth in a different way. CMEs originating close to the central meridian, directed toward the Earth, excite the biggest scientific concern. In coronagraphic observations they appear as enhancement surrounding the entire occulting disk and they were called 'halo CME'. Since the first identification by Howard et al. (1982) plenty of them were detected and now they are routinely recorded by the high sensitive SOHO/LASCO coronagraphs. CMEs are responsible for solar energetic particles (SEPs) and interplanetary (IP) shocks. For space weather investigations it is very important to predict the 1-AU arrival time of IP shocks. IP shocks, which carry 'energetic storm particles (ESPs)', can be dangerous for astronauts and spacecrafts. The first models considering arrival of IP shock were based on the observations of metric type II bursts as the indicator of solar disturbance (Smart&Shea, 1985; Smith&Dryer, 1990). The drift rate of type II burst allowed to determine the shock speeds and next to predict the time when they appear in the Earth vicinity. But it was pointed out by Gopalswamy et al. (1998, 2001b) that there is very little connection between coronal shocks and the IP shocks detected in situ by satellites. Since 1985 (Sheeley et al. 1985) it is clear that CMEs are the primary solar disturbances. Combining CMEs observations by SOHO/LASCO coronagraph and magnetic clouds observed in situ Gopalswamy et al. (2000, 2001a) and Gopalswamy (2002) developed an empirical model to predict the 1-AU arrival time of CMEs. The model was established on the fact that the velocity distribution of magnetic clouds, detected by the Wind spacecraft, was much more narrower (it was in the range 350-650km/s) in comparison with the velocity distribution of CMEs observed by SOHO/LASCO near the Sun (it was in the range 150-1050km/s). They postulated that the CMEs are accelerated due to interaction with the solar wind. Here acceleration means deceleration for fast events and acceleration for slow events. This effective acceleration was assumed to be constant over the Sun-Earth distance and was defined as the difference between the initial u and final v speed divided by the travel time t (it is time necessary to reach Earth by a given CME). They found definite correlation between the effective acceleration (a) and the CME initial speeds (u). The linear fit to data points gave an empirical formula for the effective acceleration: $a = 1.41 - 0.0035u$ (a and u are in units m/s^2 and km/s respectively) (Gopalswamy et al. 2000). CMEs detected in situ are Earth directed and SOHO/LASCO measurements subject to the projection effects. To improve the model, by minimizing the projection effects in determining the initial speed of CMEs, they used archival data from spacecrafts in quadrature (Gopalswamy et al. (2001a) and Gopalswamy (2002)). These considerations improved formula for effective acceleration and they received $a = 1.765 - 0.00429u$ and $a = 2.193 - 0.0054$ respectively. These relation can be used in the kinematic equation, $S = ut + at^2/2$, to predict the arrival time at 1 AU. It is important to note that the only free parameter requires by the models is the initial velocity. To generalize the model, Gopalswamy et al. (2001a) assumed that the effective acceleration can cease at some distance ($d1$). The best results were received when acceleration ceased at distance

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equal 0.76 AU. Although, the model is able to predict travel time with smaller error (the average prediction error=10.7), it has still fundamental shortcomings:(i) The formulas for effective acceleration, derived for archival data for limb events, were applied for later CMEs with initial speeds subjected to the projection effects. The error becomes bigger if we try to use above relations with projection correction (Leblanc et al. 2001, Goplswamy et al. 2001a).(ii) Effective acceleration, especially when we introduce the cessation of interplanetary acceleration before 1AU, is not effective to decelerate fast CMEs. The final speeds of IP clouds are almost unchanged and are distributed in the wide range of velocities (Gopalswamy 2002, Fig. 3). It is in contradiction with the beginning assumption of the model. This suggests that the effective acceleration must be bigger than the one predicted by the models. In the paper we will introduce a new formula for effective acceleration and predict the 1-AU arrival time with higher accurance. For this we use the halo CMEs for which the space velocities are determined. In the next section new formulas for effective acceleration are introduced. In the next two sections results and short summary are presented.

2. MODELS FOR EFFECTIVE ACCELERATION

We considered the whole halo CMEs recorded by the SOHO/LASCO coronagraphs until the end of 2000. If they are front side we can recognize them in the in situ magnetic field-plasma measurements as clear ejecta (EJs) or magnetic clouds (MCs). In the paper we will call both MCs and EJs as interplanetary CMEs (ICMEs). To build the model predicting 1-AU arrival time we have to; (1) select halo CME-ICME pairs; (2) determine an empirical relation between the effective acceleration and the initial speed of halo CMEs; and (3) finally use this formula and kinematic equations to obtain the transit time t. Using data from SOHO/LASCO catalog and observation from Wind satellite we were able to selected 38 HCME-ICME pairs covering period of time from the beginning of 1996 until the end of 2000. Viewing in the plane of the sky does not allow us to determine the crucial parameters defining geoeffectivness of CMEs, such as the space velocity, width or source location. Assuming that halo CMEs have constant velocities, are symmetric and propagate with constant angular widths at least in their early phase, it was developed a technique to obtain the required parameters (Michałek 2002 et al.). This technique requires measurements of sky-plane speeds and the times of first appearance of the halo CMEs above opposite limbs. This technique was applied to obtain the parameters of all the halo CMEs observed by the Solar and Heliospheric Observatory (SOHO) mission until the end of 2000. The space velocities were determined for 20 events from the all HCME-ICME pairs and their are shown in the column four. The HCME-ICME pairs with determined

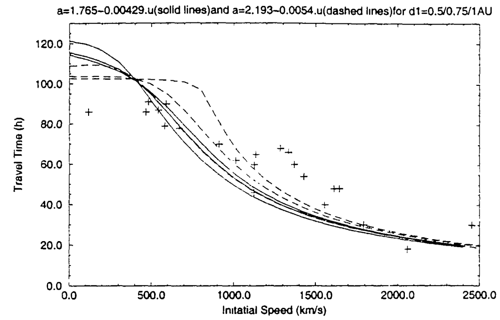

Figure 1. Comparison between predicted and observed travel times based on the acceleration profile obtained by Gopalswamy et al. (2001a, dashed lines) and Gopalswamy (2002, solid lines). For both effective acceleration profiles we show the influence of the acceleration-cessation distance (d=0.5, 0.75 and 1AU). The plus symbols denote the data points. We use only HCMEs with determined space velocities.

initial space speed, free from projection effects, are used for our considerations. In Figure 1 we show two Gopalswamy models for effective acceleration ($a = 1.765 - 0.00429$ and $a = 2.193 - 0.0054$) with different values for acceleration cessation distance $d1 = 0.05, 0.75, 1.00AU$. Scattered points represents data for our HCME-ICME pairs. It is clear that the models do not work very well for events with initial speed in the velocity range from the 1000km/s until 1500km/s. The data points in the velocity range are higher than models predictions represented by solid and dashed lines. Similar results were received by Gopalswamy et al. (2001a) when they compared models with points corrected on projection effects. This mean that predicted travel time must be larger. To enlarge travel time we can postulate stronger effective deceleration (for fast events) which should reduce the average velocity of CMEs. The effective acceleration obtained from CME-HCME pairs are plotted in Figure 2. The solid line denotes, analogously to Gopalswamy considerations, the linear fit to data points. This line defines a new profile and model for the effective acceleration $a = 3.408 - 0.0062u$. In the next section predictions for the model will be shown. When we use a such average acceleration we have to assume that whole events with different initial velocities are accelerated or decelerated all time during the travel. But it is clear that acceleration can ceases (when CME achieves solar wind velocity) at the some distance from the Sun. From this point CME should travel with constant velocity close to solar wind speed. Assuming the acceleration depends linearly on the initial speed we can derive a second new formula for CME acceleration. This formula is presented by dashed line in Figure 2. This straight line crosses two characteristic points. The first point denote CMEs with initial space velocity equal $500km/s$ which have average velocities similar to solar wind velocity and we expect that they propagate with constant speed. The second one represents the fastest event from our sample. We expect that the event, which has the final velocity higher than

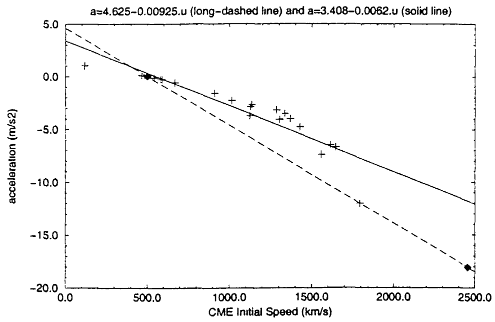

Figure 2. The effective acceleration versus initial speed of CMEs obtained for halo CMEs. The crosses denote the data points. The diamonds indicate two characteristic points. First diamond, for initial speed equal $500km/s$, represents CMEs running in the interplanetary medium with constant velocity. Second one, denote the fastest CME from the sample. The solid line is the linear fit to data points. The dashed line is the straight line crossing two characteristic points denoted by diamonds.

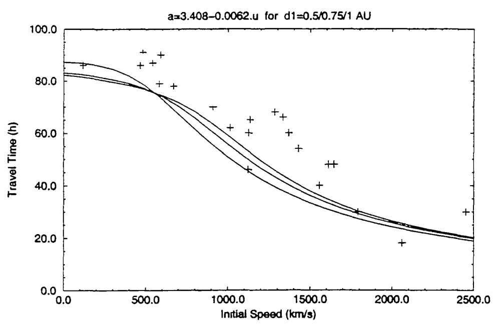

Figure 3. Comparison between predicted and observed travel time based on the acceleration profile analogous to Gopalswamy consideration with the effective acceleration $a = 3.408 - 0.0062$. The solid curve show the influence of the acceleration-cessation distance (lower-0.50AU, middle-0.75 and upper-1.00). The plus symbols denote the data points. We use only CMEs with determined space initial velocities.

the solar wind velocity is accelerated until the distance 1AU at least. These points are denoted by diamonds. The profile gives formula for average acceleration $a = 4.625 - 0.00925u$. Using this formulas we can determine traveling time for CME with a given initial space speed. In the model we assume that each CME at the beginning phase of propagation is accelerated or decelerated until it achieves velocity equal 500km/s. From this point a given CME propagate with constant velocity. This means that events with different velocities have different acceleration cessation distance. The fastest events can be decelerated until detection in situ, without cessation acceleration at any distance from the Sun. The events with initial velocity equal $500km/s$ propagate with constant velocity, similar to the average solar wind speed.

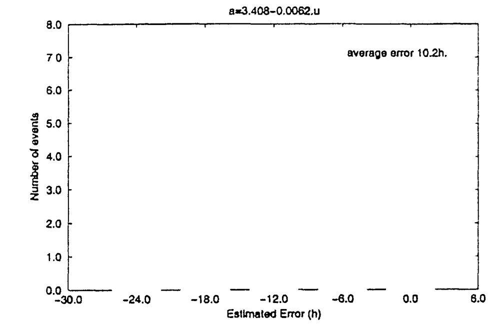

Figure 4. A histogram of the estimated error using $a = 3.408 - 0.0062u$ model, the bin size is 6 hours

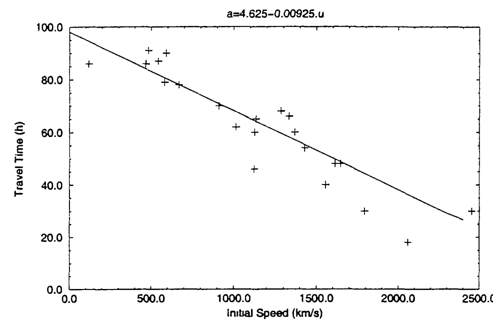

Figure 5. Comparison between predicted and observed travel time based on the transport model with the effective acceleration $a = 4.625 - 0.00925$. The plus symbols denote the data points. We use only CMEs with determined space initial velocities.

3. RESULT

We determined the travel time for the both presented models. The measured travel times versus the prediction curves for model analogously to Gopalswamy considerations but with the effective acceleration $a = 3.408 - 0.0062u$ are plotted in the Figure 3. We show the prediction curves corresponding to the cessation acceleration distance of 0.50, 0.75 and 1.00AU. The agreement between the model and the data is not good. Generally the CMEs seem to arrive later than the prediction. It is also prove in the Figure 4. It shows the distribution of estimated errors in the arrival time for the prediction curve with the cessation distance 1AU. The error has a Gaussian distribution with a peak at 12 hours. The mean error of 10.2 hours is similar the one obtained by Gopalswamy et al. 2001. To improve results we introduced model with stronger effective acceleration $a = 4.625 - 0.00925u$ and the cessation acceleration distance depending on the initial space velocity. In the Figure 5 we compare the prediction curve for the model with measured travel time. The plus symbols denote the data points. In this case, the agreement between the model and data is very good. It is also proved in Figure 6. Figure 6 shows the estimated errors in the arrival time for the prediction curve with the effective acceleration $a = 4.625 - 0.00925u$. The error has a Gaussian distribution with a peak at 0.0

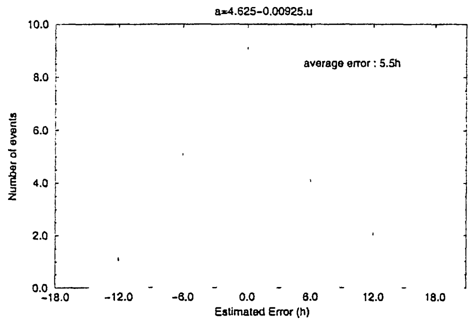

Figure 6. A histogram of the estimated error using $a = 4.625 - 0.00925$ *model, the bin size is 6 hours*

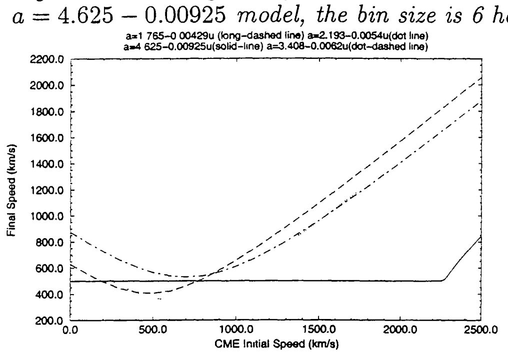

Figure 7. Final speeds of CMEs predicted from initial speed based on Gopalswamy et al.(2000) (long dashed line for d1=1AU), Gopalswamy et al. (2001, dot line for d1=1AU), the first our model (dot-dashed model for d1=1AU) and the second our model (solid line).

hours. The mean error of 5.5 hours is two times smaller than the one predicted by previous models. In Figure 7 we show the final speeds of CMEs versus initial speeds predicted by different models. The best results, with final speed approximate equal 500km/s for almost the entire range of initial speeds, are given by the our model with strong effective acceleration (solid line on the picture). The rest models give final speeds scattered in the wide velocity range. It is in contradiction with the observations.

4. SUMMARY

In the paper we have presented a new model predicting the 1AU arrival time. It was postulated, analogously to Gopalswamy papers, the effective acceleration representing the solar wind-CME interaction. The most important parameter for this purpose is the initial CME speed. Unfortunately, this is the most difficult parameter to measure for halo CMEs because the nature of coronagraphic observations. Fortunately, it was developed a new technique to obtained the necessary parameter (Michalek et al. 2002). Our considerations were based on the halo CMEs with determined the space initial velocities. We assumed that the effective acceleration due to interaction with solar wind is stronger and most CMEs achieves the average solar wind speed at some distance from the Sun. This cessation acceleration distance depend on the initial speed of CMEs. Only the fastest events (with initial speed $\geq 2000 km/s$) can be decelerated until the Earth. The model allowed to limit the estimated average error to 5.5 hours. It is two times less than for previous models. We have to point out that the simple considerations have several shortcomings: (i) Only small fraction (chosen halo CMEs) of all geoeffective CMEs have determined the space initial velocities. This means that the model must be used for events subjected to projection effect. (ii) We use the average effective acceleration depending only on the initial velocity. The real acceleration could change over all the Sun-Earth distance. It depends on the nature of friction and properties of solar wind. Ejected CMEs cross sectors defined by different solar plasma. (iii) There are observed radio signatures of CMEs interactions (Gopalswamy et al. 2001c, 2002b). CMEs can be suddenly accelerated or even 'swallowed' by another event. In this case the travel time can be unpredictable. It is clear that to improve our model we need to develop new observations techniques. Stereoscopic observations are necessary to get the CME initial speed accurately. Measurements at several points between Sun and Earth are required to achieve a realistic acceleration profile of CMEs.

In this paper we used data from SOHO/LASCO CME catalog. This CME catalog is generated and maintained by the Center for Solar Physics and Space Weather, The Catholic University of America in cooperation with the Naval Research Laboratory and NASA. SOHO is a project of international cooperation between ESA and NASA.
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